High-Temperature LPP Collector Mirror

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ABSTRACT

The EUV source output power and the collector optics lifetime have been identified as critical key issues for EUV lithography. In order to meet these requirements a heated collector concept was realized for the first time. An ellipsoidal collector substrate with an outer diameter of 320 mm was coated with a laterally graded high-temperature multilayer. The interface-engineered Mo/Si multilayer coating was optimized in terms of high peak reflectivity at 13.5 nm and a working temperature of 400 °C. Barrier layers were introduced on both interfaces to block thermally induced interdiffusion processes of molybdenum and silicon to provide long-term optical stability of the multilayer at elevated temperatures. A normal-incidence reflectance of more than 40 % at 13.55 nm was measured after heating. After initial annealing at 400 °C for one hour, no degradation of the optical properties of these multilayer coatings occurred during both long-term heating tests for up to 100 hours and multiple annealing cycles. The successful realization of this high-temperature sub-aperture collector mirror represents a major step towards the implementation of the heated collector concept and illustrates the great potential of high-temperature EUV multilayer coatings.

Keywords: Collector mirror, thermal stability, multilayer coatings, optics lifetime

1. INTRODUCTION

The output power of a high-power extreme ultra-violet (EUV) source at 13.5 nm wavelength and 2 % bandwidth as well as the source and collector lifetime can be regarded as major challenges of the EUV lithography development efforts today. Current concepts for the collector mirror (C1) configuration are mainly determined by the EUV source geometry. Grazing-incidence nested-shell Wolter collectors are commonly developed for discharge produced plasma (DPP) sources while for laser produced plasma (LPP) sources the use of normal-incidence multilayer-coated collector mirrors is a suitable choice. In order to meet the source specifications for high-volume production both C1 concepts are facing considerable collector mirror lifetime challenges. Severe mirror degradation can be induced by source material buildup on the collector, sputtering of the layer materials, source material implantation and diffusion into the layer materials, deposition of material sputtered from the source hardware, deposition of source material contaminants, EUV induced carbon growth and oxidation, thermal instability of the layer materials, and so forth. A multiple-stage debris mitigation system in combination with a collector mirror coating with a high temperature and radiation stability has to be applied to maximize the collector mirror lifetime.

Cymer's EUV source concept for beta and high-volume production tools is based on a droplet LPP source using lithium or tin as a source fuel and a high-temperature multilayer collector mirror that will be heated during operation. The concept is schematically illustrated in figure 1. The drive laser is based on two XeF excimer laser power amplifiers utilizing Cymer's XLA universal platform. As described previously [1] a hybrid system was developed where the third harmonic of a Nd:YLF solid state seed laser serves as oscillator and input to XeF power amplifiers. The target material is generated in the form of liquid metal droplets in order to reduce the amount of debris produced. The XeF laser beam is focused through a central opening in the collector mirror onto the droplet target to create a microplasma emitting

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Emerging Lithographic Technologies X, edited by Michael J. Lercel,
Proc. of SPIE Vol. 6151, 61514A, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.662138

intense radiation. The mirror collects a portion of the EUV radiation emitted in the direction of the incident laser beam and redirects it towards the intermediate focus (IF) point. The mirror can be heated from the backside during operation to support evaporative removal of material deposited on its surface. For lithium a temperature in the range of 350 °C – 400 °C is sufficient to provide conditions where the evaporation rate exceeds the influx rate substantially. The present status of the source integration effort is summarized in [2].

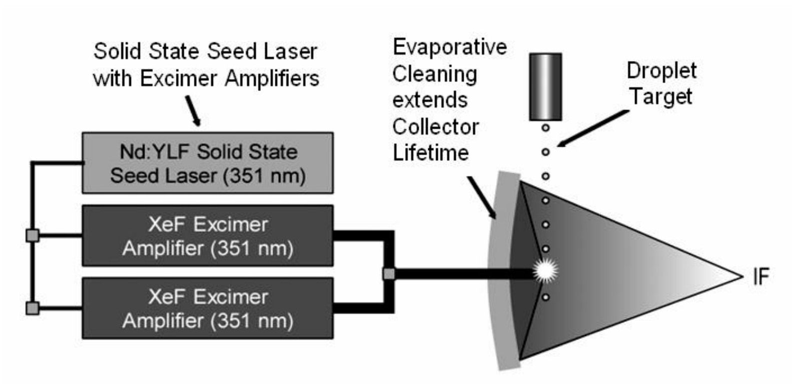

Fig. 1: Cymer's high-volume production EUV source concept.

The proper choice of materials for the LPP collector coating depends on various factors, such as the required optical properties, the operational environment, and the material compatibility. Due to their excellent optical properties Mo/Si multilayer coatings are widely used for applications at around 13.5 nm wavelength at normal, near-normal and oblique angle of incidence. However, a serious problem of these Mo/Si multilayers is the structural instability of their interfaces at elevated temperatures above 200 °C limiting their application as coating of a C1 mirror. The heated collector substrate and the exposed collector mirror position in close vicinity to the plasma would cause thermal and EUV-radiation induced damages for a pure Mo/Si coating resulting in a substantial reflectivity loss and thus a strongly reduced collector mirror lifetime. Hence, a high-temperature multilayer coating with sufficient resistance to radiation damage has to be applied.

2. HIGH-TEMPERATURE MULTILAYER DEVELOPMENT

The optical and structural properties of a number of promising candidate high-temperature multilayer systems were studied in detail by several groups previously [3-7]. Based on our initial tests [8], a high-temperature multilayer coating with thin barrier layers of high inertness (X) was developed to enhance the thermal stability of the Mo/Si multilayer structure. The interface-engineered Mo/X/Si/X multilayer mirror was designed to combine both a high normal-incidence reflectivity above R = 60 % at 13.5 nm and a superior long-term thermal stability of up to 500 °C. Figure 2 shows the evolution of the EUV reflectance curves of coated Si-wafer test samples after isothermal annealing at T = 400 °C and T = 500 °C, respectively, for 1, 10 and 100 hours.

A relative wavelength shift of $\Delta\lambda/\lambda$ = + 0.4 % and + 0.5 %, respectively, was found without any considerable reflectivity drop after annealing at 400 °C and 500 °C for 1 hour. Pre-annealing at a temperature of T ≅ 400 °C for 1 hour stabilized the internal structure of this type of multilayer mirror. The optical properties of pre-annealed Mo/X/Si/X multilayer mirrors were constant (± 0.4 %) in the temperature range from 20 °C to 500 °C after long-time heating (τ = 100 hours). Structural investigations of the multilayer volume by transmission electron microscopy (TEM) showed a high layer contrast without any signs of interdiffusion (Fig. 3).

The surface structure of the Mo/X/Si/X multilayer mirror on a Si wafer substrate both after deposition and after annealing was investigated by atomic force microscopy (AFM). Surface measurement results showed a slight increase in the high spatial frequency roughness (HSFR) from 0.12 nm rms to 0.14 nm rms (Fig. 4).

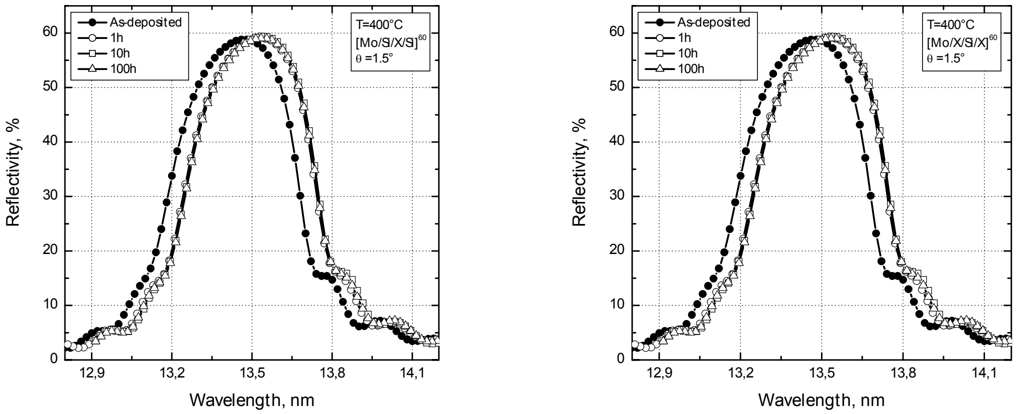

Fig. 2: Reflectivity of Mo/X/Si/X after deposition and annealing at T = 400 °C (left) and T = 500 °C (right) during 1, 10 and 100 h.

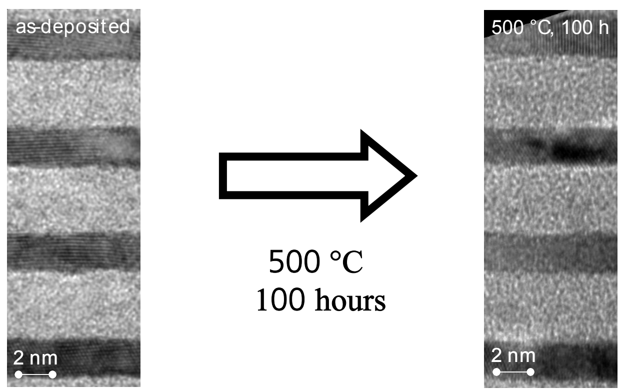

Fig. 3: TEM of Mo/X/Si/X multilayer mirror as deposited (left) and after annealing at 500 °C for 100 hours (right).

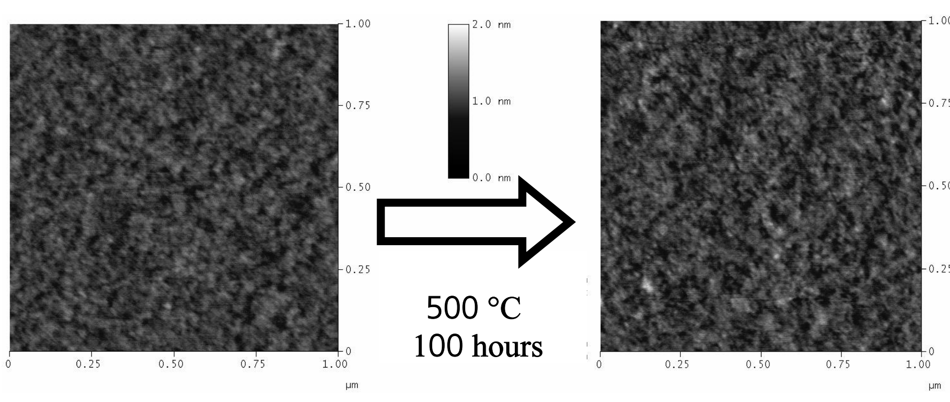

Fig. 4: AFM surface characterization of Mo/X/Si/X multilayer mirror as deposited (left: rms roughness 0.12nm) and after annealing at 500 °C for 100 hours (right: rms roughness 0.14 nm).

The combination of high EUV reflectivity and high long-term thermal stability at temperatures up to 500 °C underline the promising potential of these new high-temperature Mo/X/Si/X multilayers as coatings for the heated LPP collector.

3. COLLECTOR MIRROR COATING AND ANNEALING

Several ellipsoidal sub-aperture collector mirror substrates with an outer diameter of 320 mm, representing a solid collection angle of 1.6 sr, have been realized. Design considerations, requirements, collection geometry as well as optical and opto-mechanical design are summarized in [9]. The substrate material is silicon carbide (SiC). The mirror shells have a central aperture for laser beam focusing. Here, we report on the results obtained with the first collector mirror. Prior to the coating process the SiC collector substrate surface has been characterized by AFM in a wide lateral spatial frequency range up to a scan width of 100 µm. The HSFR of the collector surface was measured in scan ranges of 1 µm x 1 µm (Fig. 5) and 10 µm x 10 µm (Fig. 6). Due to the limited AFM sample stage size all measurements were taken at a distance of approximately 50 mm from the outer edge of the substrate.

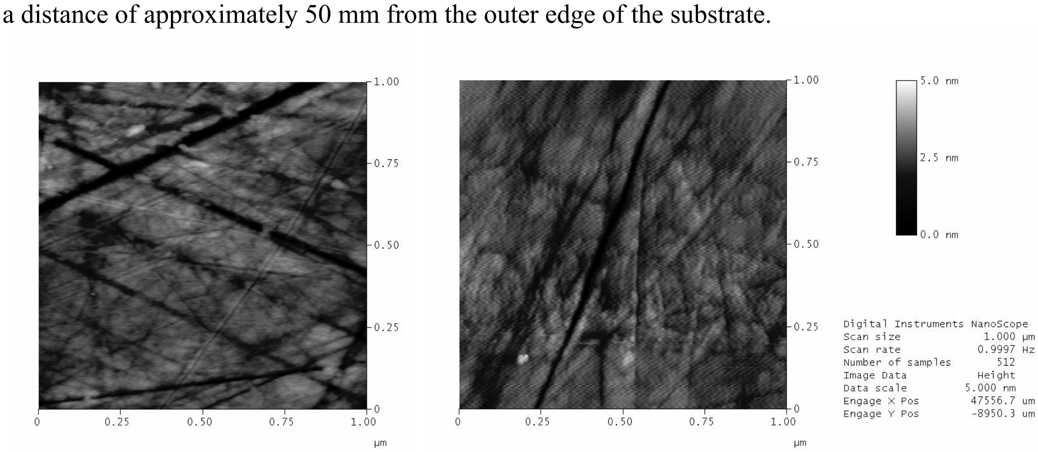

Fig. 5: AFM measurement of the collector mirror substrate. Scan width: 1µm x 1µm: σ_{rms} = 0.67 nm (left), σ_{rms} = 0.47 nm (right).

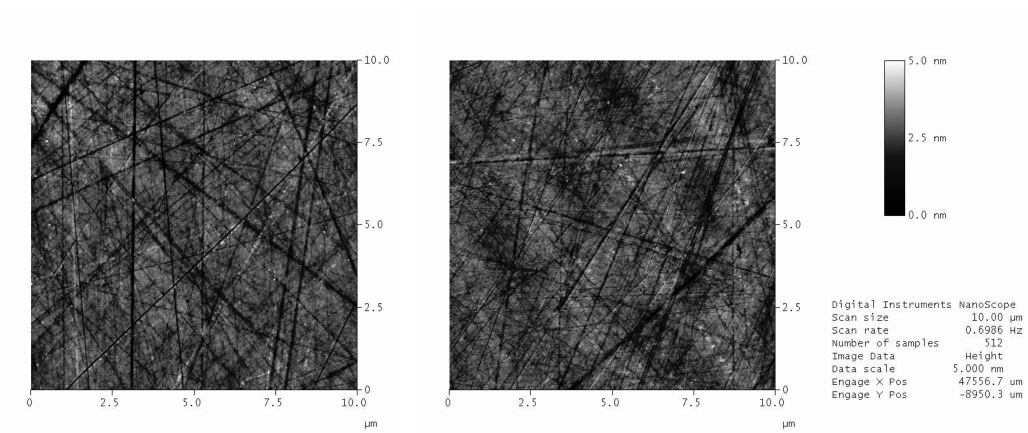

Fig. 6: AFM measurement of the collector mirror substrate. Scan width: 10µm x 10µm: σ_{rms} = 0.62 nm (left), σ_{rms} = 0.59 nm (right).

As a result of the substrate surface characterization by atomic force microscopy it can be concluded that the average HSFR value is about σ_{rms} = 0.6 nm. Polishing scratches with statistical directional distribution can be regarded as the dominating surface structure. Prior to the coating process it has been assumed that the substrate surface roughness will result in a reflectivity drop of only a few percent.

The coating of the ellipsoidal collector mirror substrate with a laterally graded high-temperature interface-engineered Mo/Si multilayer was realized with the large-area deposition system NESSY (Fig. 7). The dc magnetron sputtering system is equipped with four rectangular magnetrons with 600 mm x 125 mm sputter targets each allowing the deposition of substrates up to 650 mm in diameter. Alternatively, the simultaneous coating of two Ø 450 mm substrates or three Ø 300 mm substrates can be realized. The target-substrate-distance is variable and allows the installation of

moving shutters to realize lateral thickness gradients of the sputtered multilayer. Substrates up to Ø 450 mm can be loaded through a load lock chamber keeping the base pressure well below $8*10^{-9}$ mbar.

Special efforts have been made to construct the cathodes. Different configurations of the magnets have been successfully realized in order to assure highest flexibility for different coating materials in terms of homogeneity requirements and target utilization. All magnetrons work stable at a working pressure of $< 7*10^{-4}$ mbar in an argon atmosphere.

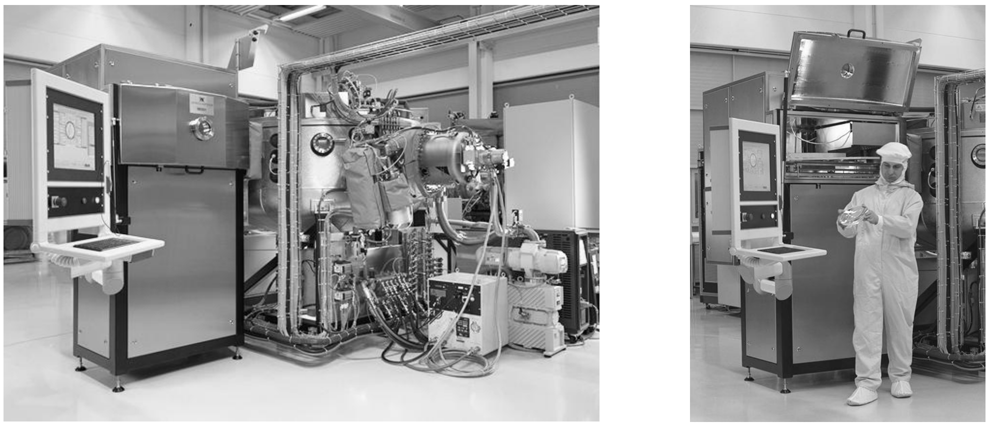

Fig. 7: DC magnetron sputtering system NESSY (left) with substrate load lock (right).

The deposition parameters as well as the multilayer design parameters were optimized in terms of both high thermal stability (1st priority) and high reflectivity (2nd priority) by coating Si test samples on a test sample holder. Due to the variation of the angle of incidence on the collector mirror substrate from about 5 degrees close to the inner clear aperture (CA) to about 17 degrees close to the outer CA a lateral thickness gradient had to be applied to the interface-engineered high-temperature Mo/Si multilayer. The lateral multilayer gradient was optimized in order to meet the specified peak wavelength of (13.5 ± 0.1) nm. Figure 8 compares the ideal multilayer gradient with the experimental data measured on test samples. The error bars in Figure 8 correspond to a relative multilayer period error of $\Delta d/d = 0.74$ % and hence to the specified peak wavelength of (13.5 ± 0.1) nm.

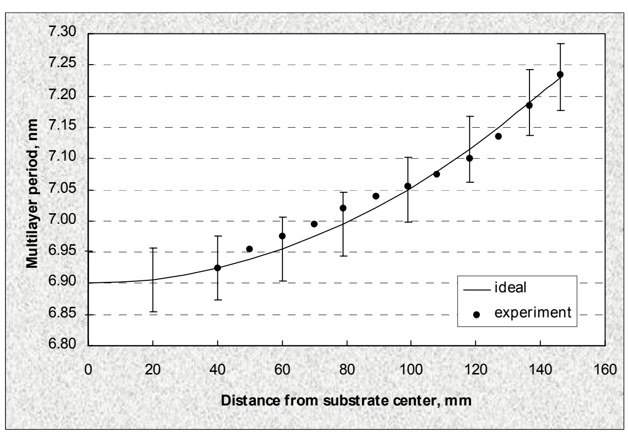

Fig. 8: Multilayer gradient: Ideal case and experimental data.

The mirror substrate was cleaned and mounted in a special holder for coating. A super-polished silicon wafer was also mounted on this holder at the location of the central aperture of the mirror substrate to serve as a witness plate during the coating and annealing processes. The layer deposition process was carried out according the recipe developed in the optimization procedure. A capping layer was deposited on the multilayer structure as protective top layer.

After deposition the multilayer-coated collector mirror was annealed at 400 °C for one hour in order to achieve layer stabilization. The annealing was carried out in a vacuum chamber under UHV conditions (p = $5*10^{-6}$ mbar) to prevent oxidation of the top layer. A heating rate of 2 K/min and a long cooling time were chosen to minimize the risk of substrate damage by thermally induced stress. The temperature measured close to the sample surface fluctuated between 396 °C and 406 °C during annealing at the 400 °C target temperature. A photograph of the coated and annealed high-temperature collector mirror taken during processing in the clean room is shown in figure 9.

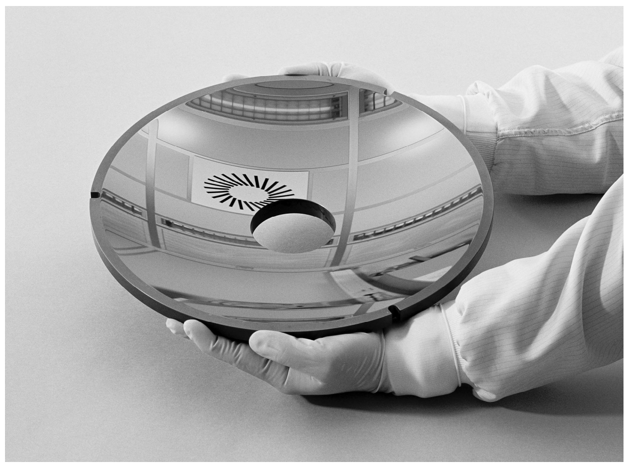

Fig. 9: High-temperature LPP collector mirror.

4. EUV REFLECTIVITY MEASUREMENTS

The EUV reflectivity of the ellipsoidal 1.6 sr mirror and the central Si witness plate was measured with the EUV reflectometer of the Physikalisch-Technische Bundesanstalt Berlin (PTB) at the electron storage ring BESSY II. The reflectometer is designed for at-wavelength metrology of full-size EUVL optics with a maximum weight of 50 kg and an outer diameter of up to 550 mm. An absolute uncertainty of 0.1 % can be achieved for the measured peak reflectance with a reproducibility of 0.05 %. For the center wavelength an uncertainty of 2 pm is obtained with a long-term reproducibility of 1.1 pm and a short-term reproducibility below 0.06 pm. A detailed description of the reflectometry facility can be found in [10].

The EUV reflectivity of the high-temperature mirror was measured with s-polarized light for a series of points along four orthogonal lines over the collector CA within a wavelength range from 12.5 nm to 14.5 nm. The spot size at the sample surface had a diameter of ~ 1.5 mm. The respective angle of incidence was adjusted for each measurement point as calculated according to the optical mirror design and the distance from the focus to the mirror surface. The maximum reflectance values obtained at all measured positions within the mirror CA are shown in figure 10. The measured peak reflectance is predominantly above R_p = 40 %, the maximum reflectance value is R_{max} = 43.2 %.

Although the measured reflectance shows some variation for different positions on the mirror, the peak values are nevertheless of similar magnitude for both small and large radial positions, with a small decrease only for the data obtained at r = 140 mm. This indicates the general accuracy of the layer gradient optimization. Apart from one low value the maximum reflectance varies between 36 % and 43 % within the CA. Since the substrate is rotated during

deposition the reflectivity fluctuations for different mirror locations are attributed to the surface conditions of the substrate rather than to the coating. The measured reflectivity curves versus wavelength obtained along one line within the CA are shown in Figure 11. They exhibit slightly asymmetric profiles with centroid wavelengths near 13.55 nm. The full-width at half-maximum is generally > 0.45 nm.

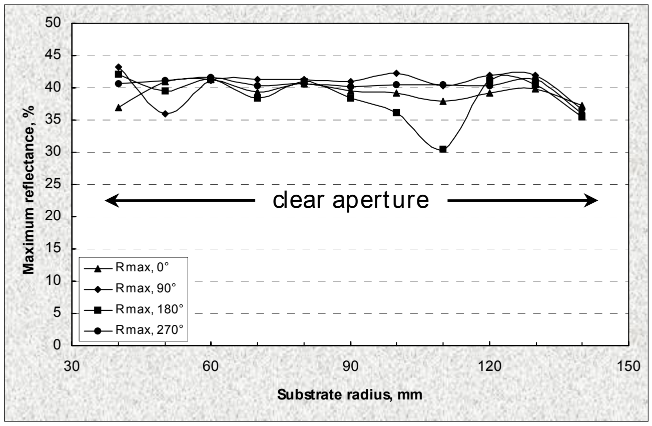

Fig. 10: Peak reflectance of high-temperature collector mirror at various locations on the mirror. Measurements: PTB Berlin.

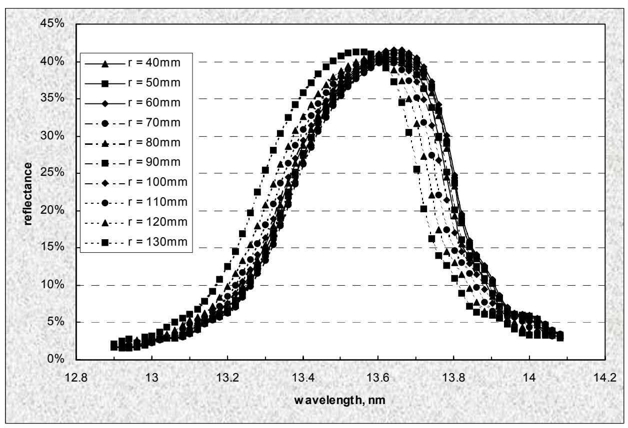

Fig. 11: Reflectivity curves at different collector mirror radii along one line within clear aperture. Measurements: PTB Berlin.

For the Si witness plate positioned at the center of the collector during the deposition process a Mo/X/Si/X peak reflectance of R = 54.1 % at near normal incidence was measured (Fig. 12, left). This test sample had a HSFR of less than 0.15 nm rms. When using a correlated-film growth model (where the roughness of the layer n depends on the roughness of the layer (n-1)) to simulate the reflectivity on the Si witness sample with the IMD software [11] a very good agreement was obtained between measurement and simulation (see Fig. 12, left). The corresponding multilayer design parameters such as Si layer thickness, Mo layer thickness, barrier layer thickness, interface roughness and layer density can be obtained from the simulation. According to calculations a reflectivity drop of about 5 % can be expected due to the influence of the capping layer that has been deposited on top of the high-temperature Mo/X/Si/X. Thus, the result on the Si witness plate corresponds to the expected maximum reflectivity level of R ≅ 60 %.

When using the same roughness model to simulate the reflectivity behavior measured for the SiC collector mirror at 60 mm from the mirror center, no exact correspondence was found between measurement and simulation (Fig. 12, right). The reflectivity drop introduced by a substrate roughness of $\sigma \sim 0.65$ nm would still result in a peak reflectivity

of R > 50%, in contrast to the measured values. It may be presumed that the substrate surface roughness may not be the only reason to explain the observed difference of the reflectivity level between the Si witness sample and the SiC mirror. However, the modeling has so far not provided data to simulate the reflectivity curves R = f (λ) for the collector mirror with sufficient accuracy.

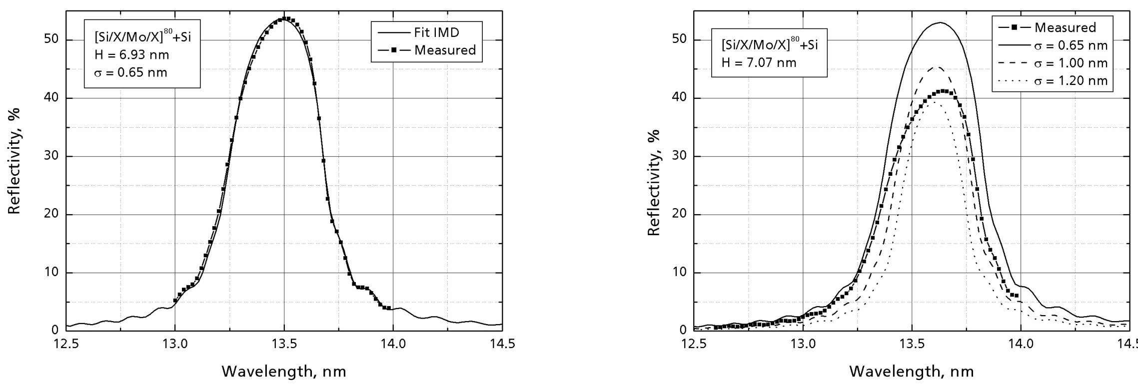

Fig. 12: Reflectivity of Si test sample (left) and at 60 mm from center of SiC collector mirror (right) and corresponding simulations.

5. SUMMARY AND CONCLUSION

A high-temperature multilayer collector mirror for LPP sources has been realized for the first time. With an outer diameter of 320 mm this is the largest EUVL collector mirror coated to date. With a solid angle of 1.6 sr the mirror represents a sub-aperture of a 5 sr full-size mirror. The high-temperature multilayer coating is based on a capped interface-engineered Mo/Si system showing a long-term thermal stability of up to 500 °C. The average peak reflectivity of the collector mirror was measured to be near 41 % at 13.55 nm. A Si witness plate was coated in the same deposition run and showed a larger peak reflectivity of 54.1 % at 13.5 nm. Future work will be focused on reflectivity enhancement by further optimization of multilayer design and deposition processes as well as the optimization of the lateral thickness gradient.

ACKNOWLEDGEMENTS

The authors would like to thank the members of the IOF coating project team for their support, in particular Wieland Stöckl and Michael Scheler for their technical support and Marcel Flemming for delicate AFM measurements at the collector mirror edge. We are grateful to Frank Scholze, Christian Laubis, Christian Buchholz and Heike Wagner for carrying out EUV reflectivity measurements at PTB, Berlin. We also thank Ute Kaiser, University of Ulm, for providing us with TEM data of the MLM coatings.

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